N64-19902

CODE-1

NASA CR-53882

25p.

# Westinghouse Research Laboratories



FINAL REPORT - APPLIED RESEARCH ON ELECTRO-MAGNETO-STRICTIVE VIBRAGYRO.

G. R. Douglas, G. Mott, D. D. Skinner,
J. H. Thompson

Report 64-969-570-R1
April 1, 1964

PROPRIETARY CLASS 2

Research Report 64-969-570-R1<br>PROPRIETARY CLASS 2

April 1, 1964

FINAL REPORT

# APPLIED RESEARCH ON ELECTRO-MAGNETO-STRICTIVE VIBRAGYRO

January 8, 1963 to March 7, 1964

National Aeronautics and Space Administration

Contract NASw 580

G. R. Douglas
G. Mott
D. D. Skinner
J. H. Thompson

Approved by: A. Nellin

Westinghouse Electric Corporation
Research and Development Center
Pittsburgh 35, Pa.

# Table of Contents

## List of Illustrations

Research Report 64-969-570-R1
PROPRIETARY CLASS 2

April 1, 1964

# FINAL REPORT

# APPLIED RESEARCH ON ELECTRO-MAGNETO-STRICTIVE VIBRAGYRO

January 8, 1963 to March 7, 1964

## I. INTRODUCTION

There is a definite need in space applications for a small, light weight, rugged, reliable, low powered, long-lived gyroscope to be used for the damping of oscillations in spatial reference control systems. A vibratory type of rate gyroscope is a promising candidate to meet these requirements.

Westinghouse has designed a solid state vibragyro operating at ultrasonic frequency and having the above assets. The major problem remaining to be solved is the lowering of the threshold response, or minimum detectable rate signal level. This is now limited by crosstalk noise in the output circuit, which results in an inconsistent null signal.

A one-year program of applied research leading to identification and reduction of the cross-talk components, and thus an improvement in the signal-to-noise ratio, was undertaken for NASA at the beginning of 1963. During the course of this program changes in configuration of the gyro have increased the Q of both the input and output modes of vibration by a factor of 3, thus raising the signal level by a factor of 9. Changes have also been made to reduce the crosstalk and improve the signal-to-noise ratio. Additional improvements are in sight and recommended for a continuation of the program.

## II. BACKGROUND

In 1954 development work was begun at the Westinghouse Research Laboratories on a tuning fork type vibratory rate gyroscope operating in the audio frequency range. This work was continued by the company's Air Arm Division starting in 1956. Much was learned from this development work -- primarily that all reaction forces for both driven and response modes must be developed in a balanced vibratory system and not transferred to the frame or base. This is necessary for consistency in the resonant frequency, in the sharpness of resonance, and in the balance of the device.

In the spring of 1960, work was begun at the Research Laboratories on a solid state vibragyro utilizing one of the newer ferroelectric ceramics available. The idea became practical upon the design of a solid body which had two independent vibratory modes which could be tuned to the same frequency and which could be coupled by the Coriolis effect. In order for the two modes to have no mechanical cross-coupling, one would have to be a shear mode and the other a mode associated with a change in volume. The configuration which evolved, namely a hollow-cylinder or tube, admirably suits these requirements. It is very symmetrical and has balanced modes of vibration which lend themselves to the purpose at hand.

Since 1961, the Air Arm Division has been working on a development program for the Air Force based on the use of piezoceramic both for the driving means and for the readout information. In other words, they are using a ceramic tube which is poled in one portion to provide driving means and poled differently in another portion to detect the response mode of vibration. Meanwhile, work has progressed at the Research Laboratories, most recently under NASA contract, on models which utilize magnetostrictive material for the response. This form of vibragyro uses two concentric tubes cemented together. One tube is piezoceramic for the driving means; the other tube is magnetostrictive material for the readout function. This report describes recent progress on this combined electro-magneto-strictive vibragyro.

## III. THEORY OF OPERATION

The driven mode of vibration of the hollow cylinder or tube forming the vibragyro may be referred to as the push-pull circumferential expander mode. This is a mode where at one instant the circumference at one end of the tube is larger than its static value while the circumference at the other end is smaller. At a later instant the opposite is true. It could be described as a conical vibration of the cylinder. The motion is sinusoidal (simple harmonic motion) and the operating frequency is the motional resonant frequency of this mode. The correct driving frequency is most accurately controlled by substituting the piezoceramic tube for the crystal in a crystal-controlled oscillator circuit (Meacham Bridge, etc.)

The moments of inertia of the two ends of the tube are being modulated out of phase at the driving resonant frequency. If the cylinder is rotated about its axis with respect to inertial space, Coriolis or gyroscopic forces act on the moving particles trying to conserve angular momentum and produce a twisting couple between the two ends which results in a torsional vibration of the cylinder. The length of the tube is tailored so that the torsional resonant frequency is near the push-pull circumferential driving resonant frequency, the driving resonance being determined primarily by the mean diameter of the tube. Thus the torsional (response) vibration amplitude will be proportional to the angular rate of motion of the vehicle. The phase of this response motion reverses with respect to the driven vibration when the angular rate changes from clockwise to counterclockwise.

Most of the models constructed under this contract have been composite cylinders made of two concentric tubes, the inner driving tube being made of piezoceramic lead-zirconate-titanate and the outer readout tube being made of magnetostrictive "A" nickel. The operating frequency is in the neighborhood of 100 kilocycles per second. The output signal must be amplified, phase compared, and demodulated before use as a damping signal in a position control system.

## IV. PROBLEM AREAS

The main problem has been to achieve a consistent null signal in the readout channel. Although there is theoretically no mechanical cross-coupling between the two modes of vibration if the geometry is perfect, asymmetry in elastic, damping, or inertial forces can couple one mode into the other one. There can also be electrical and magnetic cross-coupling forces in the vibrating body, as well as capacitive and electromagnetic coupling between input and output circuits. This cross-coupling between modes leads to cross-talk in the output signal channel. It is a spurious rate signal having the same frequency and cannot be distinguished from the true rate signal by the detector. It can be balanced out electrically under particular conditions but will not remain balanced or nulled if the operating frequency, temperature, or other conditions change. This will be described in greater detail in Section 7. The inconsistency in the null signal affects the absolute accuracy of the device.

Another problem area is that of determining the threshold response or minimum detectable rate. This can be affected by fluctuations in the gyro output signal or in a nulling signal if used. It can also be affected by random fluctuations or noise in the detector circuit. Increasing the sensitivity of the gyro will improve the signal-to-noise ratio so far as the random noise is concerned.

## V. CONFIGURATION STUDIES

Previous experience with vibratory rate gyros indicated that crosstalk would be a major problem. To minimize this effect, the configuration has been kept as simple and as symmetrical as possible. The use of electrostrictive principles for driving and magnetostrictive principles for readout eliminates most of the direct electrical coupling between input and output. Experience gained from work on this contract

points to the use of the magnetostrictive material (nickel) for the bulk of the vibrating material. This is advantageous since the nickel is more homogeneous, more consistent in elastic constants, can be machined to better symmetry, and has a higher sharpness of resonance (Q).

It is advantageous to use piezoceramic for driving means since it has a better electromechanical coupling factor and can serve as its own frequency control.

In quest of a higher Q, it was decided to make both the piezoceramic and the magnetostrictive tubes resonant in both modes at the same frequency prior to bonding together. Since the nickel tube has the higher Young's modulus, it must have a larger mean diameter and length than the ceramic. Thus the nickel must be the outer of the two concentric tubes. Figure 1 shows this construction. The ceramic tube has ring-shaped driving electrodes at each end to stimulate the push-pull circumferential expander vibration. The ceramic tube is epoxied within the nickel tube which vibrates with the ceramic. The torsional (response) vibration produces an alternating flux component in the nickel which generates a signal voltage in the readout coils. The gyro is mechanically supported at the nodal circle by a neoprene O-ring held in a groove in the coil form.

A boundary surface represents a dis-continuity in the dynamics of particle motion. Therefore it was surmised that a solid cylinder with fewer boundary surfaces would have purer particle motion and less mechanical cross-coupling. This was tested on a solid cylinder of barium titanate as shown in Figure 2. Unwanted coupling between modes resulted due to limitations placed on poling direction by the shape. A solid cylinder cannot be poled either radially or circumferentially and thus does not lend itself to versatility in design.

An all-magnetostrictive model was built and tested since a simple nickel tube offered the best mechanical symmetry. This model

is shown in Figure 3. The disadvantage of this design is that there is direct electromagnetic field coupling (transformer action) between input and output windings, even though they are perpendicular. Also the input impedance does not change appreciably at resonance and the gyro cannot control its driving frequency without extra feedback sensors. Gyroscopic response was noted but the level was down about two orders of magnitude from the other models. The signal level could be raised by winding more turns on the readout coils, but this would raise the transformer action crosstalk.

On the combination nickel-PZT model, one component of crosstalk was a result of direct torsional stresses applied to the gyro by the push-pull-circumferential driving means. This component was nulled by changing the electrode shape and electric field pattern in the PZT so that there was no net axial component of voltage gradient in the PZT.

The basic shape of a hollow cylinder or tube with its independent shear and volume modes of vibration has so far shown itself superior to any other general shape.

## VI. MATERIAL STUDIES

No effort has been made to develop a new material but only to use the most suitable existing material. The lead-zirconate-titanate ceramics are continually being improved by the manufacturers. They seem to be the most suitable piezoceramic for this purpose, as their characteristics are relatively stable with respect to temperature changes, and they have good piezoelectric characteristics. The ceramic used in this program has been PZT-7A, except for the solid cylinder barium titanate model.

The magnetostrictive material used has been "A" nickel, annealed at $600^{\circ}$ C. for one hour. This is the optimum annealing for

making use of its magnetostrictive properties when dealing with residual rather than external means of polarization.

## VII. CROSSTALK CHARACTERISTICS

The crosstalk can be studied best with the gyro slightly detuned, i.e. with the two resonant frequencies several hundred cycles per second apart. Reference to Figure 4 shows that the crosstalk associated with the driven or push-pull-circumferential mode of vibration resonates at 97.74 kilocycles per second with a mechanical Q of 600 in this case. The relative amplitude variation and phase shift of this crosstalk component appearing in the output are as shown.

The crosstalk associated with the torsional mode peaks at 97.52 kilocycles per second with a Q of 1200. Its relative amplitude and phase variation versus drive frequency are also shown. In addition, there is a crosstalk component (e.g. mechanical cross-coupling) which is associated with both modes and peaks up at both resonant frequencies, with a total phase shift of $360^{\circ}$ as the frequency is swept.

Figure 5 shows the phase of various crosstalk components relative to the push-pull-circumferential driving force. Note that the Coriolis response undergoes a $360^{\circ}$ phase shift as the driving frequency is swept through both resonant modes.

## VIII. NULLING TECHNIQUES

Two general approaches to the crosstalk problem can be taken. One is to trim up or balance the gyro itself, so that there is no crosstalk. This is the best, but most difficult, solution. The other approach is to null out the crosstalk in the output channel. This should be done in such a way that the null is maintained if the frequency is varied somewhat, so that a departure of the driving frequency from the gyro resonant frequency is not critical.

It is possible by changing the flux pattern in the nickel tube to trim the gyro so that at a particular driving frequency there is no crosstalk. This means that the crosstalk was not eliminated but that the summation of crosstalk components from various sources was zero at that frequency. A drift in frequency unbalanced the null since the different components do not have the same phase vs. frequency characteristic. For good performance, each component must be nulled individually by a different means. This has not been achieved as yet.

A scheme to null the crosstalk in the output channel is shown in Figure 6. A crystal to detect the push-pull-circumferential motion was cemented to the end of the nickel tube. This signal was amplified and applied to a torsional shear crystal to null the mechanical cross-coupling in the gyro. The PPC signal was also added in the output channel to null that component of crosstalk (magnetic assymmetry). This scheme did not look good due to lead effects and construction problems.

Figure 7 shows another scheme for nulling the crosstalk. It has been tried only partially. The signal (1) is obtained from a bridge in the driving circuit of the gyro. The bridge is balanced off resonance. At resonance the unbalance signal is proportional to the resonant motion of the driven mode. This signal is fed to the mixer, and also applied to a torque winding inside the nickel tube. The drive voltage is also applied to a torque winding inside the nickel tube. The readout winding external to the nickel tube then detects the Coriolis signal plus crosstalk plus two trim signals, one (2) associated with the torsional resonance only and the other (3) associated with both the driven resonance and the torsional resonance. Thus three trim signals whose phase and amplitude must be adjusted would be used to null the crosstalk. Only the (1) signal has been tried experimentally as shown in Figure 8.

## IX. THRESHOLD MEASUREMENTS

An attempt was made to determine the threshold response of the vibragyro; i.e. the minimum detectable change in angular rate sensed by the gyro. Extreme care must be taken to keep random noise at a low level in these measurements since a net voltage gain of 120 db. or more must be used in the detection system. The circuit shown in Figure 8 was used for this purpose. The gyro output signal was first nulled, then amplified in the transistor pre-amp. It was then demodulated and amplified in the transistorized d-c amplifier. This output signal was filtered and fed into another d-c amplifier and recorder.

The gyro was placed on a rate table as shown in Figure 9. This table has spring hinge pivots, a voice coil driver, and is heavily damped by eddy current damping, so that the motion is smooth. The driver is energized from a function generator with either sinusoidal or triangular wave displacement signals at a frequency from .01 cycle per second or more, for threshold measurements, up to several hundred cycles per second for frequency response measurements. The lowest rate recorded was 50 degrees per hour as shown in Figure 10. The actual threshold in this case was less than 50 degrees per hour. If defined as the value of signal equal to the noise level then the threshold was about 20 degrees per hour.

## X. ADMITTANCE MEASUREMENTS

Admittance plots for two slightly different models are shown in Figures 11 and 12. The conductance at the series (motional) resonant frequency $f_s$ is about 200 micromhos. With a driving voltage of 5 volts the input power would be $50 \times 10^{-4}$ watts. The input mechanical Q as determined from these admittance plots is about 1000. An admittance plot of the output mode (magnetostrictive) could not be taken as the admittance does not change significantly at resonance.

## XI. PROJECTED DEVELOPMENT

The experience gained in this program points to the use of metal as the major portion of the vibrating system for the following reasons. Metal is more homogeneous than ceramic and thus more consistent in density and modulus of elasticity throughout the material. Metals also have a higher Q (sharpness of resonance) than ceramic.

The present models could be modified to increase the signal strength by using ferrite around the readout coil to increase the flux linking the coil. This would likewise increase the crosstalk component due to unwanted torsional motion, but would not increase the crosstalk components coming from other sources. It also would not increase the random noise.

Another approach now considered promising is to make the main tube out of passive, non-magnetostrictive metal. The push-pull circumferential vibration could be driven by two small piezoceramic rings near the inside middle of the tube. The torsional readout could be a piezoceramic or magnetostrictive ring placed around the outside middle of the tube. Thus the readout ring would detect the torsional strain at the middle (where it is maximum) rather than the strain in the entire tube. Since the driven motion is minimum at the middle any crosstalk due to this motion would be minimized.

It appears now that the best metal to use for the main tube is Ni Span C, which has chracteristics such that the density variation with temperature is matched with the elastic modulus variation with temperature so that the resonant frequency will not be temperature dependent. This metal has the additional benefit of a low coefficient of thermal expansion: Since lead-zirconate-titanate also has a low coefficient this will minimize fracture problems due to differential thermal expansion of the metal and ceramic parts. Of course this is no problem anyway if the design is such that the ceramic is never subjected to tensile forces.

It is not possible to predict the course of development too far in the future as it must proceed step by step. No development of material will be attempted but the best material for a particular design will be selected. The principal effort, of course, will be to reduce the crosstalk and thus improve the consistency of the null signal. This will increase the accuracy and lower the threshold response.

S

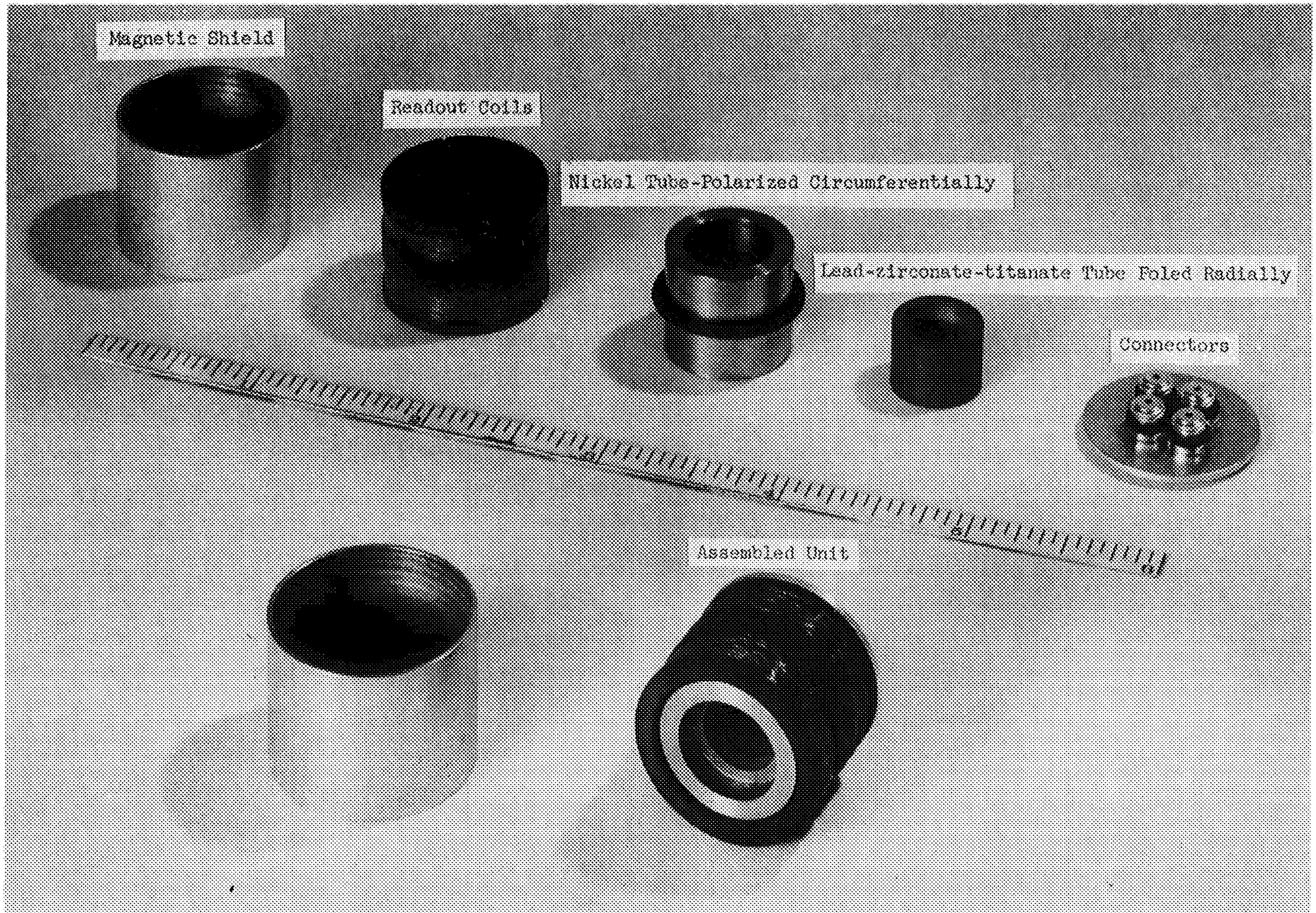



Figure 1 - Nickel-Ceramic Vibragyro

CLM 26943

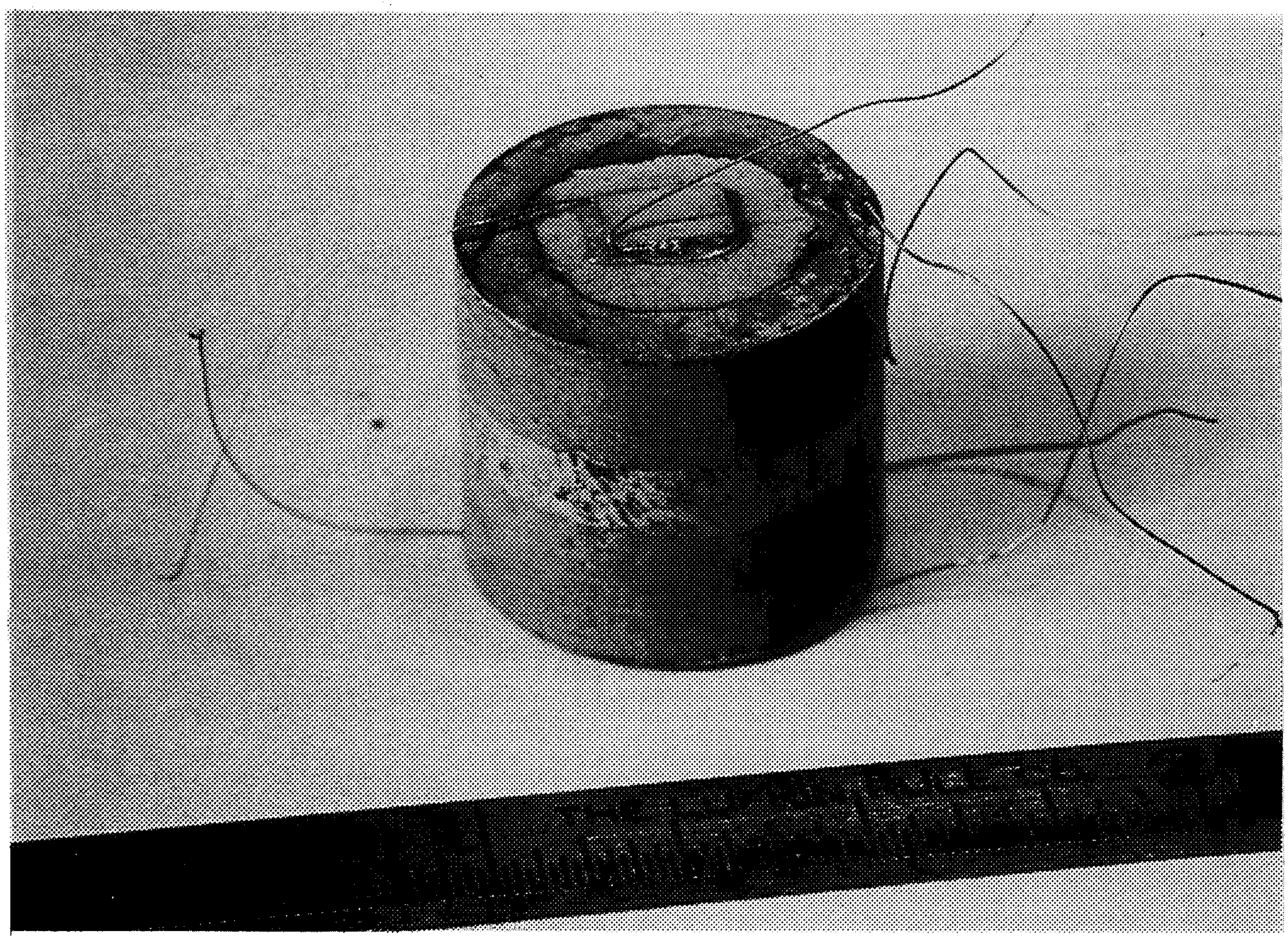


Figure 2

Solid Cylinder Model

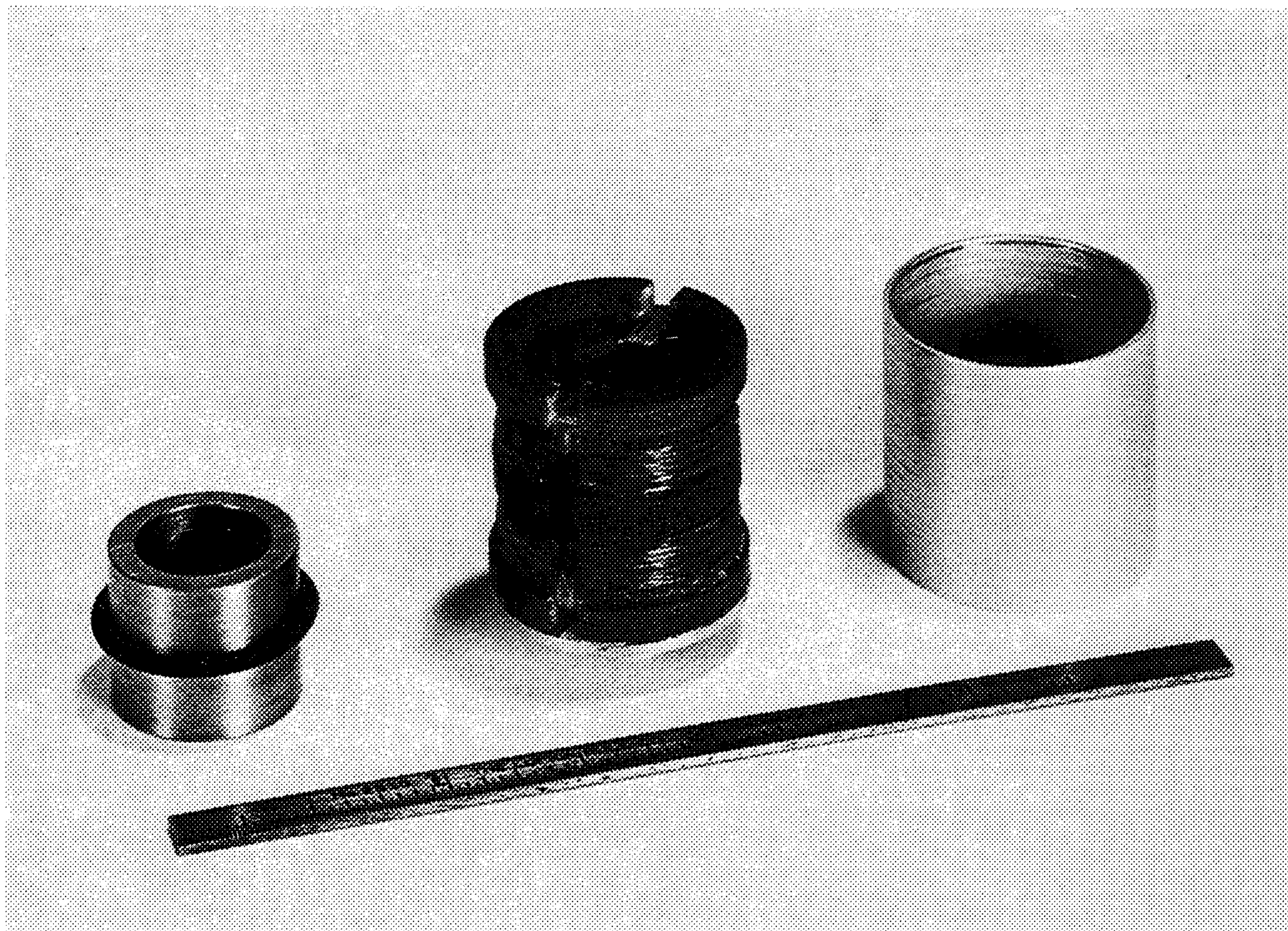


Figure 3

Magnetostrictive Model

CURVE 570255-A

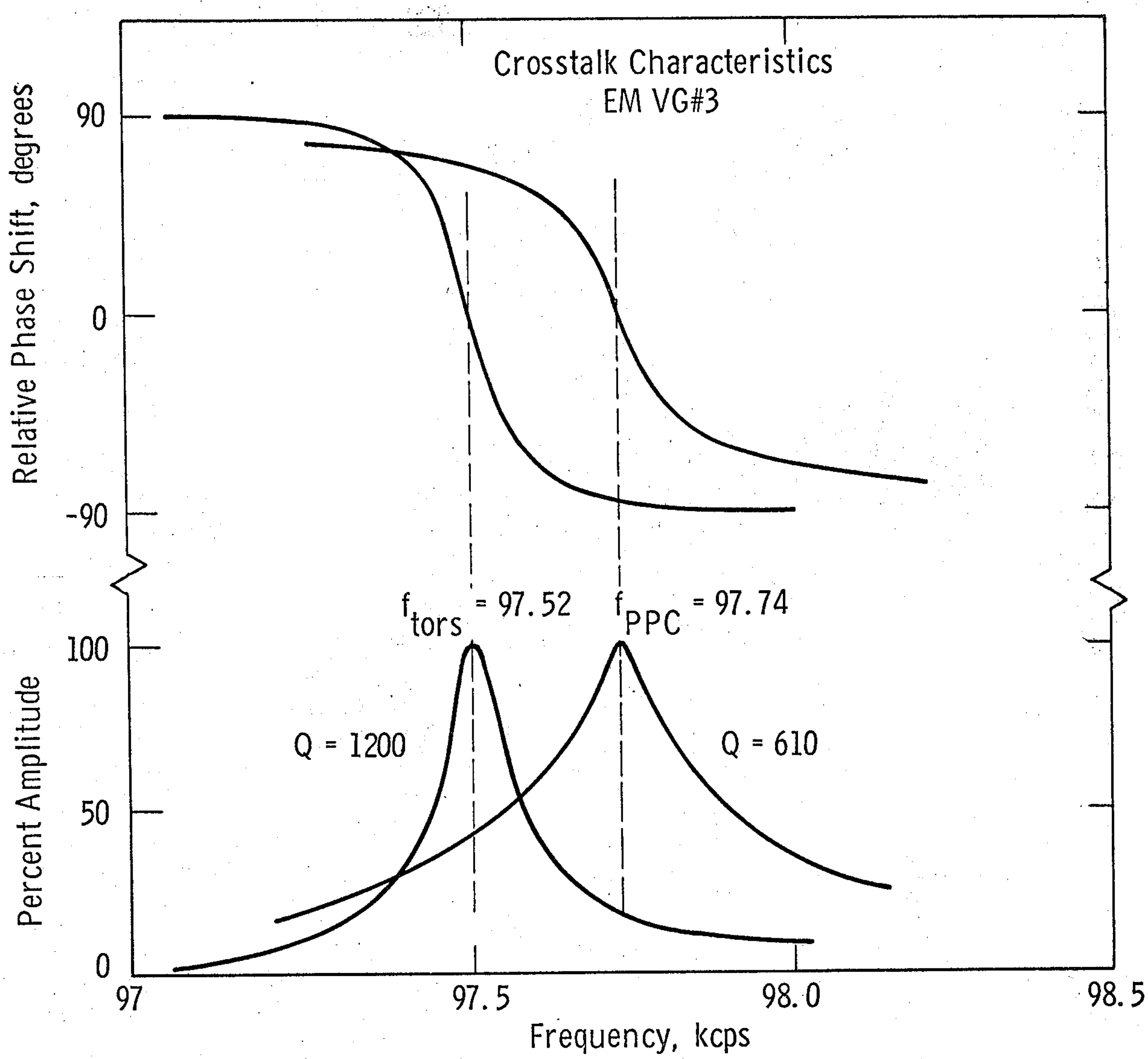



Fig. 4—Resonant modes in vibragyro

CURVE 570256-A

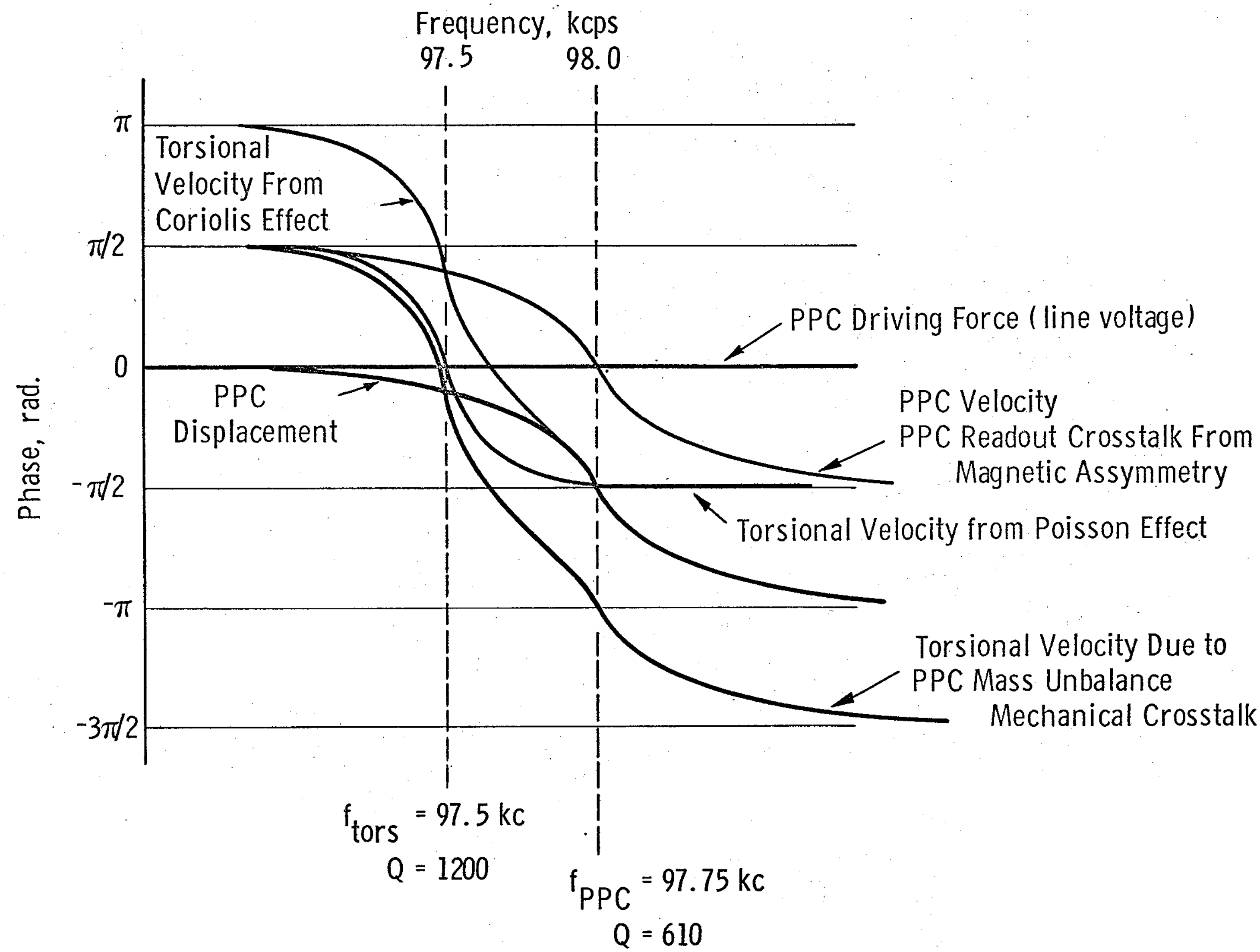
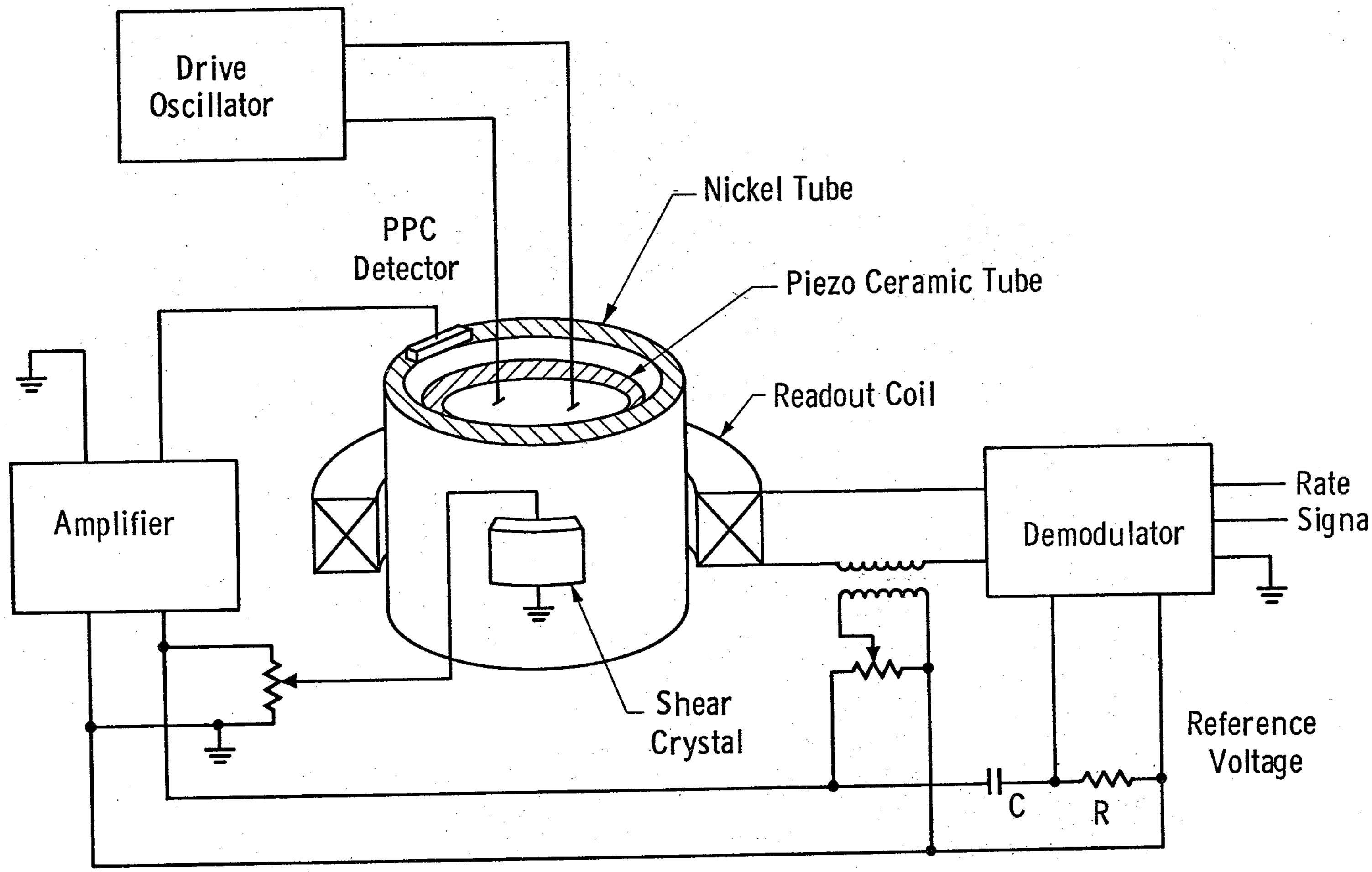



Fig. 5—Crosstalk components

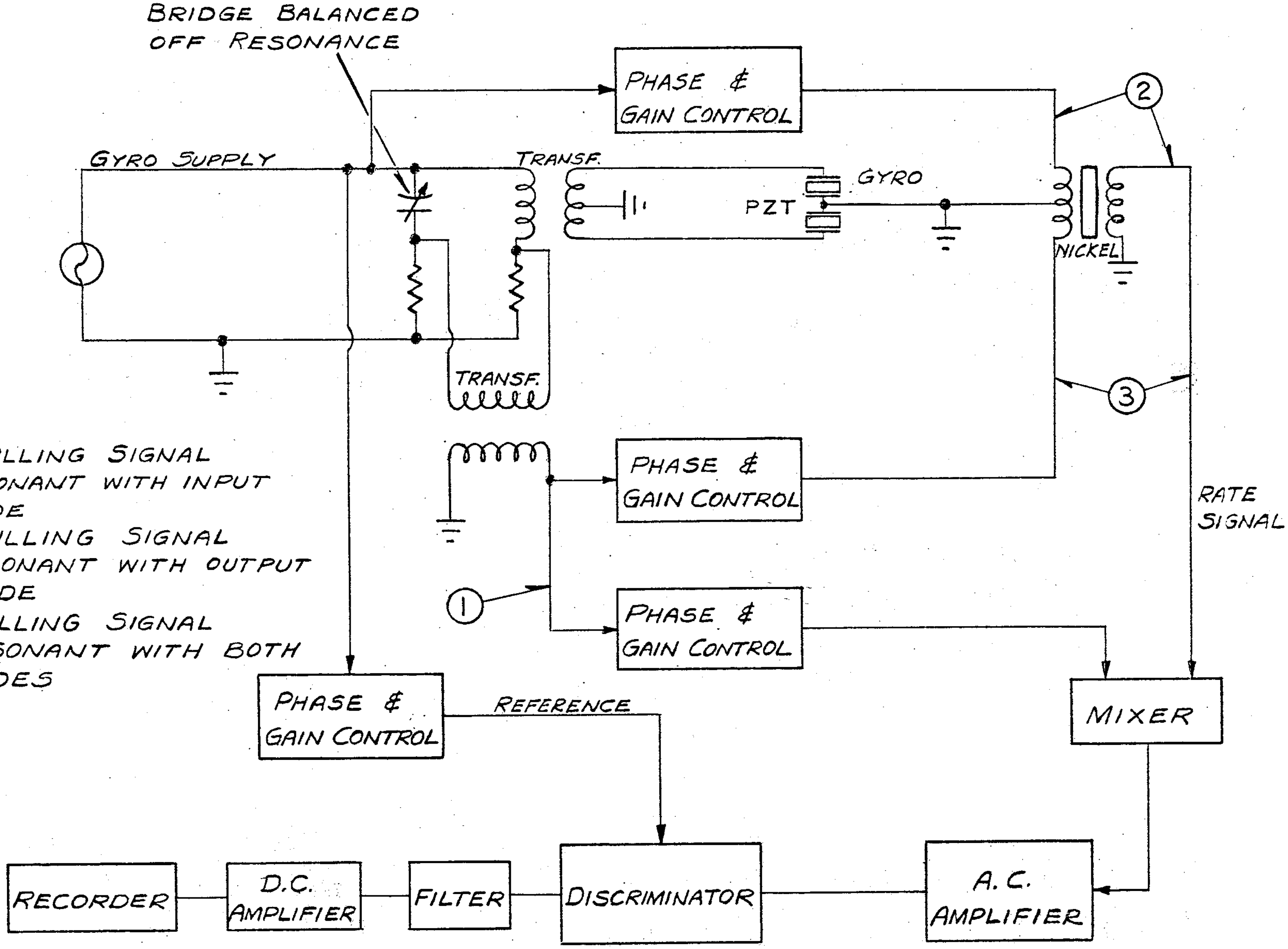
DWG. 626A828




Vibragyro cross-coupling signal cancellation

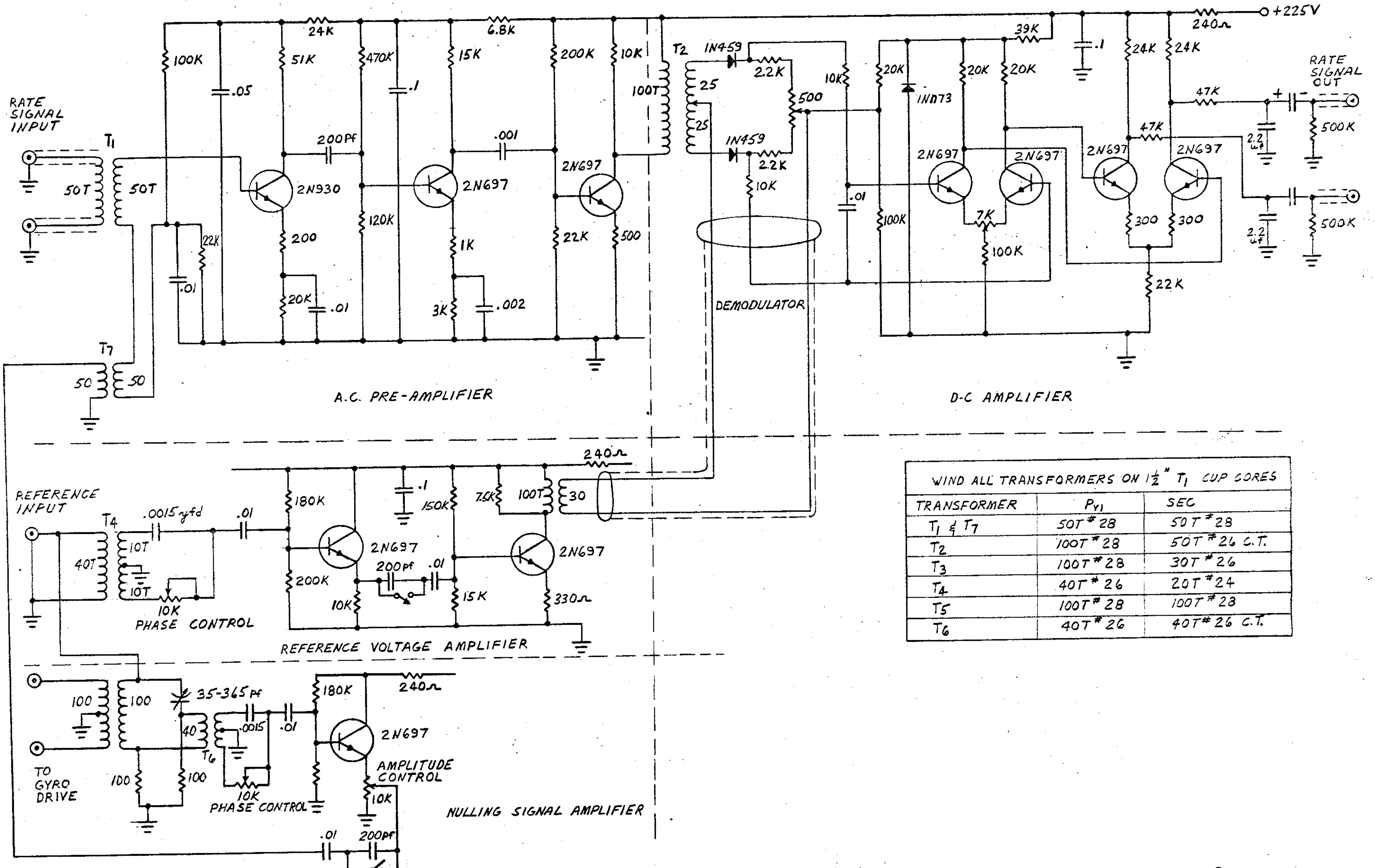
Fig. 6

743A877




1 NULLING SIGNAL RESONANT WITH INPUT MODE
2 NULLING SIGNAL RESONANT WITH OUTPUT MODE
3 NULLING SIGNAL RESONANT WITH BOTH MODES

FIGURE 7 VIBRAGYRO NULLING CIRCUIT




WIND ALL TRANSFORMERS ON 1½" $T_1$ CUP CORES

| TRANSFORMER | $P_{r1}$ | SEC |
|---|---|---|
| $T_1$ & $T_7$ | 50T # 28 | 50T # 28 |
| $T_2$ | 100T # 28 | 50T # 26 C.T. |
| $T_3$ | 100T # 28 | 30T # 26 |
| $T_4$ | 40T # 26 | 20T # 24 |
| $T_5$ | 100T # 28 | 100T # 28 |
| $T_6$ | 40T # 26 | 40T # 26 C.T. |

S. O. 1690-54501 D.
IT. 1 CHANGE

REF. DWG.

**WESTINGHOUSE ELECTRIC CORPORATION**

TITLE PHASE SENSITIVE DETECTOR

DIMENSIONS IN INCHES—DO NOT SCALE DRAWING | SUB. 1

DFTM. Wróbel 4-3-69 APPD.
CHKD. APPD.
SUPV. APPD.

117C560

RESEARCH LABORATORIES CHURCHILL BORO. PITTSBURGH 35, PA., U.S.A.

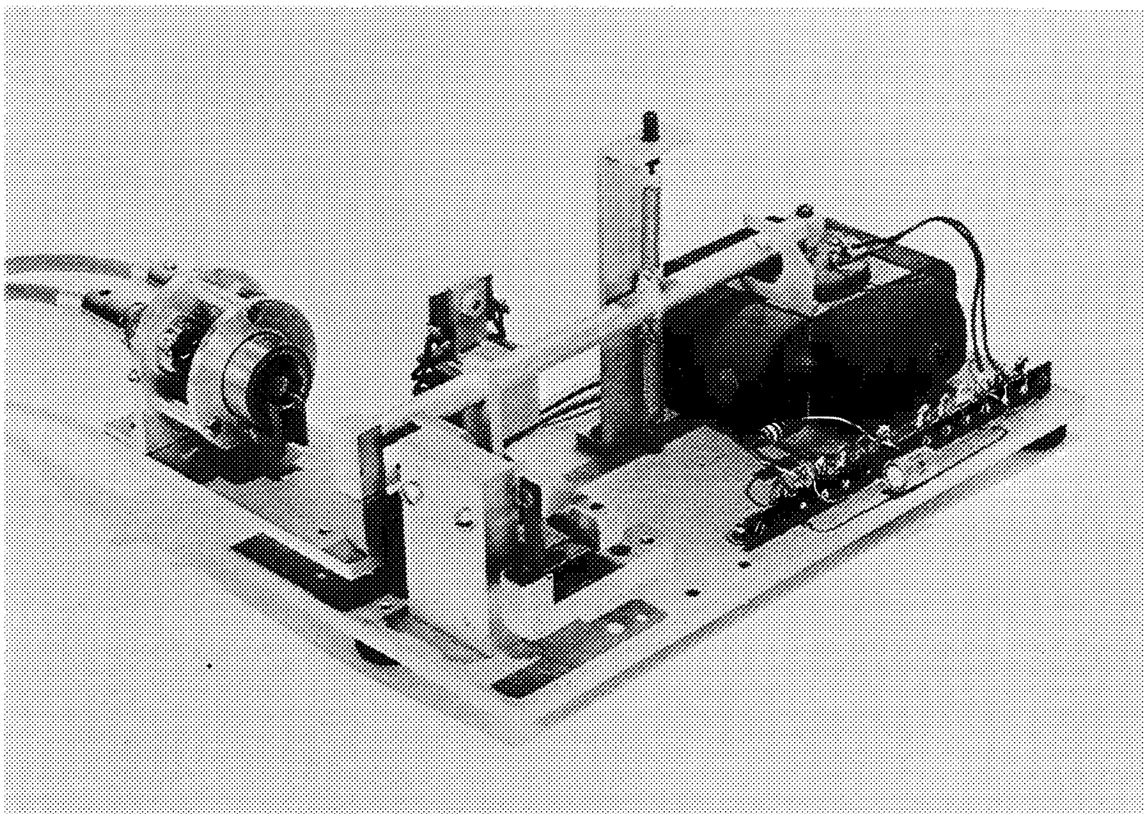


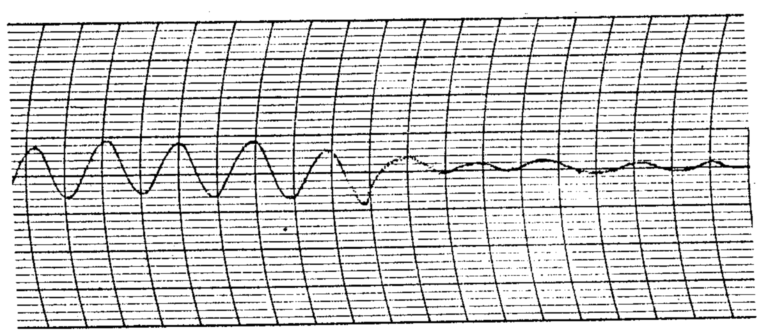
Figure 9

Cyclic Rate Table

RM 20696

Threshold response measurements on Vibragyro

Input: Simple harmonic motion with 2 sec. period



500 deg/hr. 50 deg/hr.

Figure 10

Threshold Response

## Distribution List

Office of Electronics and Control
Code REC, NASA Headquarters
Washington 25, D. C.
(25 + genessee)

Washington Sales Office
Defense and Space Products
D. Anderson

Baltimore Air Arm
Mail Stop 446
D. W. Roese

Mr. George A. Griner
Pgh. Contract Management Office
216 Old Post Office Bldg.
Pgh. 19, Pa.

Mr. W. G. James, ASRMCE-1
Flight Control Laboratory
Aeronautical Systems Division
Wright-Patterson Air Force Base,
Ohio

Los Angeles Sales Office
Rod Titcomb

R and D Center

T. Eldridge
A. Nelkin
J. H. Thompson
G. Mott
C. H. Jones
K. A. Oplinger
P. H. McAuley
Research Library Documents Office - for File
Leo G. Harper - bulletin